REV 0[1]; March 13, 2007

Physics 15b, Lab 5: Variable Voltage Power Supply

Due Friday, April 13, 2007

Attachments: LM317 Data Sheet excerpt attached

Help Labs This lab is another that you can do in your dorm room, if you like. We will offer "help labs," though, as usual:

- Wednesday 6-9 p.m.
- Thursday 3-9 p.m.

You are welcome at any of the help lab hours.

Contents

1 Purpose

1. To build a variable voltage regulated power supply.

2. To begin to understand negative feedback.

[1] Revisions: cap color corrected to tan (10/02).

2 Background

2.1 Why Add a Voltage Regulator?

You have already built a d.c. power supply, using a bridge rectifier and smoothing capacitor. For some purposes, such a simple supply is quite adequate. For example, it will do fine as a battery charger or for running a d.c. motor. However, for powering electronics, and for other laboratory uses, it has several disadvantages:

- In spite of the filter capacitor, its output will fluctuate at 120 hertz when the supply is asked to deliver appreciable current. The capacitor will drain between its twice-per cycle chargings.

- If the current drawn varies, the output voltage will vary, i. e., the supply has an appreciable internal "output" resistance.

- If the power-line voltage varies, the output voltage will vary, since it is related directly to the peak-to-peak power-line voltage. Therefore, fluctuations in the line voltage (like those that cause lights to dim) will be reflected at the d.c. output.

- Finally, for many laboratory purposes it is desirable to have a d.c. supply with a variable voltage. To achieve this with a simple rectifier, you must use a variable transformer to change the input voltage. This is an expensive and bulky solution compared to the one used by the power-supply circuit that you are about to build.

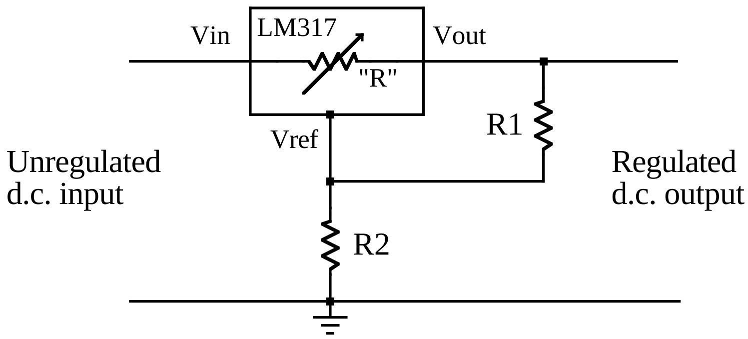
2.2 How a Voltage Regulator Works

Very Generally: Negative Feedback

Your variable voltage supply is based on a sophisticated and very effective integrated circuit used as a *feedback controller*. This control principle is basic, in the research lab as well as in homes and industry (not to mention your own body: a clever feedback scheme works pretty well to hold your body temperature constant, despite wide variations in ambient temperature!). The household thermostat mimics your body's regulator: a sensor produces a varying output as the temperature changes (sometimes the sensor puts out an electrical signal; sometimes it puts out mechanical motion). This output is compared against a preset *target* value, a level you set at the thermostat–perhaps by turning a knob. When the *measured* output is found to be below the *target* value, the thermostat turns the heater on. When the output is above the *target* value, the thermostat turns the heater off. To describe this scheme more generally: the actual value of temperature is compared to the desired value; the difference, an *error signal*, then is used to try to reduce the error (for example, by turning on the heat, if the error signal shows that the house is too cold). Incidentally, this example, the house thermostat happens not to fit the most general model, because the thermostat's output can achieve only the extremes: ON or OFF. Engineers call such regulation ”bang-bang” (with their usual aptitude for vivid, simple language). The regulator that you will meet in this lab is more subtle; it is capable of driving the output up or down *slightly*. This behavior fits the more general case of *negative feedback*.

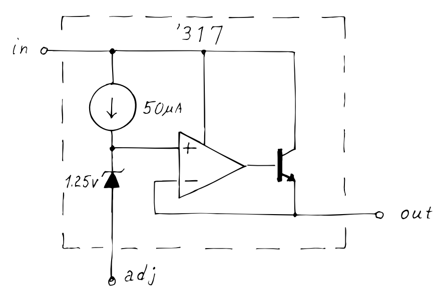
More Particularly: a particular regulator, the LM317

Now back from this excursion into the general notion of feedback: let's turn to the *integrated circuit* ("I.C." or "IC") regulator that you will use in your power supply. The main parts are shown in the diagram below. (*Note*, by the way, that the terminal labelled "V_{ref}" in the figure below is called "Adj" or "Adjust" elsewhere in these notes and in the '317 data sheet.) Here is a typical use of the '317 regulator: we provide two resistors, to set the output voltage:

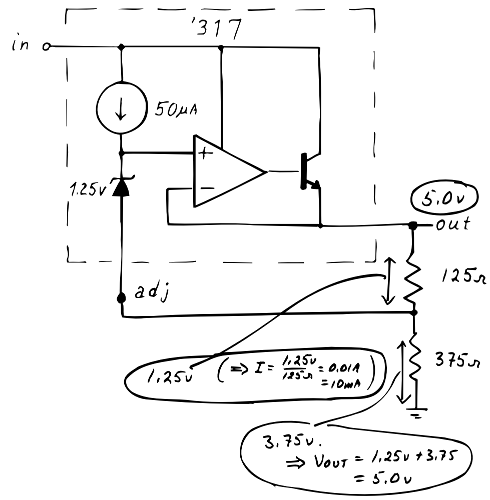


Note: Vin, Vout, Vref measured with respect to ground

And here's a peek inside–a peek that reveals that the variable resistor shown in the figure above does not very accurately represent what's going on: in fact, what's varying is the current passed by a *transistor*. A transistor, as its name suggests, resembles a *resistor* with a *transfer* characteristic–that is, it lets one control what happens at the output terminals by feeding the input terminals (a *pair* of terminals, in each case).



That odd-looking diode labelled "1.25V" is a *zener* diode that begins to conduct at its labelled voltage, and thus provides a stable *voltage reference* for the circuit. Now, that "peek inside" will be more helpful if we show it wired as in the typical circuit that we showed first. Here is the "transparent" '317 plus a couple of resistors chosen to provide an output of 5.0V:



The unregulated input is the somewhat-ripply d.c. output of your bridge rectifier. The LM317 regulator I.C. tries to hold at equal voltages the inputs to the triangle gadget: an "operational amplifier." Soon you will see more of this device; for now, we'll leave its operation mysterious.

In order to achieve that goal, the LM317 is obliged to put 1.25 volts across the 125-ohm resistor (R1 in the general figure), since we have planted a 1.25-volt *voltage reference* over to the left. The LM317 is single-mindedly concerned–perhaps *obsessed* puts it better–to maintain that 1.25V difference between OUT and ADJUST. We can exploit this obsession to get a wide range of output voltages from the '317.

The simplest scheme would be to *ground* the ADJ terminal. That would give a fixed 1.25V OUT. In the example above, we have instead done what is more typical: we have coaxed the '317 into giving us a higher output voltage. To do this, we simply planted a second resistor, of 375-ohms (R2 in the general figure), so as to raise the voltage at the ADJ terminal. The 1.25V across R1 determines a current, by Ohm's Law (10 mA, in this case) and that current in turn determines a voltage across the lower R that depends on the value of that R, of course (again, nothing fancy: just Ohm's Law at work). In this case, the 10mA in the lower R drops 3.75V to give us 5.0V out.

Here's an alternative way of describing the circuit: you may prefer to think of it as a voltage divider, and look at the ratios of the two resistors, R1 and R2. If you look at it that way, then the fact that R2 = 3R1 tells us that we'll get 3 X 1.25V across R2, and again you would predict a circuit output of 5.0V. The difference between the two ways of describing what's happening lies only in whether we choose to speak explicitly of the *current* (we did that, in the first description) or prefer to leave the current implicit and speak only of the ratio of voltage drops in the two resistors (such an implicit use of current exploits the fact that the currents in the two resistors are *equal*. (*Are* the currents *exactly* equal?. No. By how much do they differ?)

In your power supply, you will use R_1 = 360 Ω, and R_2 will be a pot used as a variable resistance, with values from 0 to 5 $k\Omega$. The value of V_{out} determined from the equation above will vary with the pot setting, from 1.25 volts when R_2 = 0 to 18.6 volts when R_2 = 5 $k\Omega$. However, V_{out} can't exceed V_{in}, and must be a few volts lower. The specifications for the LM317 (these appear on the "spec sheet" or "data sheet," mentioned below) states that this voltage difference (called *dropout voltage*: the voltage -difference below which the output "drops out") must be at least 1.5 volts. So, the '317's output will not exceed about 18.5V, if the unregulated input to your circuit is 20V.

The complete *data sheet* for the LM317 (*several sheets*–but called a "data sheet," nevertheless) appears at the end of this write-up. Here you're likely to find a lot more information than you want; but you may be curious to see what a data sheet looks like. Incidentally, in case you do start studying the specs, we are using the *T* package (SUFFIX T, on the spec. sheet). Some of the graphs are even intelligible!

To summarize, for a given setting of the pot R_2 the '317 maintains a particular regulated output voltage, so as to hold the voltage across R_1 at 1.25 volts. Ideally, doing this makes the output independent of input voltage fluctuations, including 120 Hz *ripple*, and also independent of output current. So, this electronic replacement for a "battery pack" [2] should show *zero* internal *output resistance*. By changing the setting of the pot, you can control the output voltage. As an added bonus, the LM317 is set to limit the output current to less than about two amperes regardless of what you connect to the output, even a wire connected as a short circuit to ground. Even fancier, the '317 monitors its own *temperature* and shuts itself down when it gets too hot! (I.C. designers can't resist throwing in one more nifty feature: it's not hard, once they're already putting dozens of transistors into the 60-cent part.)

Of course, the *ideal* is not quite met; the LM317 does not regulate perfectly; does not hold the output absolutely constant. Within the design operating region there are small residual effects, reduced by enormous factors from the unregulated rectifier supply (a little *ripple*, for example survives–but reduced by a factor of about 10,000. This *good* region for the power supply is defined by the range of voltages and currents appropriate to the LM317 and your bridge rectifier.

3 Procedure

3.1 Building the Supply

The Regulator IC: LM317

The drawing below shows the regulator I.C. with its *heat sink* mounted on it (really a heat radiator, to help remove power by convection). The picture shows the IC with its smooth side away from you and its plastic side with labeling on it toward you. The picture also shows the pin layout, which is essential for wiring the circuit correctly. The heat sink is shown mounted with its side fins pointing toward you, but that is not important. Your heat sink is of the slide-on type. The most common cause of a non-working supply is wrong connections to the regulator, so check carefully. **Do not confuse the actual pin layout with the circuit diagram of the LM317 in page 2**. (There is yet another drawing of the pin layout on the data sheet, page 167.)

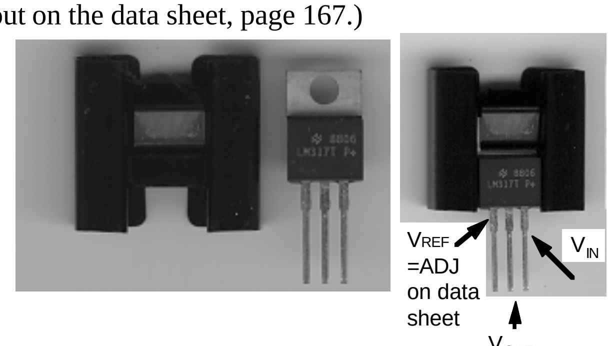
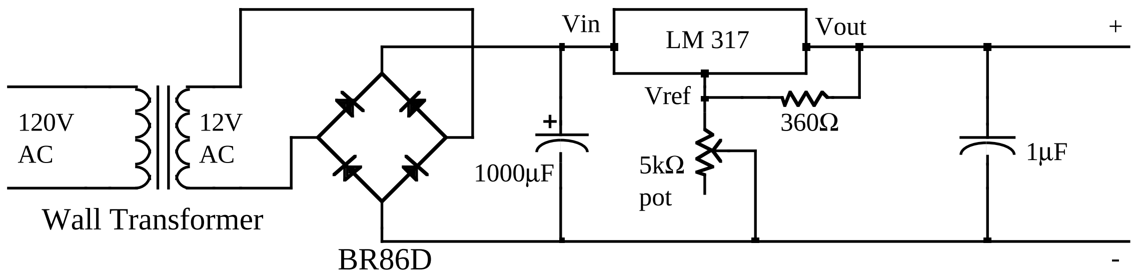


Figure 1: Pinout of LM317 regulator, and its heat-sink

[2]But don't let our likening this to "battery pack" lead you to think that this integrated circuit can produce an output larger than its input. It cannot. It "attenuates" (shrinks) a voltage fed to it, cleverly adjusting the amount of shrinkage so as to hold the output voltage at the value the user has selected.

Applying the LM317 IC: complete circuit for regulated supply

Wiring the Circuit Below is the circuit diagram. Collect all the parts you will need. The 1 μF capacitor (small, tan or blue, rectangular, labeled 105M, not polarized), not discussed so far, is to filter very fast fluctuations which the regulator can't handle. The 5k pot is the one with the brown or blue plastic and metal base. A minor aesthetic challenge is to wire it so that when you turn it clockwise the output voltage increases. (Should its resistance be 0 or 5000 ohms for maximum voltage?) Notice that the pot is used here as a variable resistor, and not connected the way you used it before, as a voltage divider.



Last time you started by building the bridge rectifier, which is the left part of the diagram, along one edge of your circuit board. Just continue along that path to complete the supply. Put all the parts on one side of the board, sticking their leads through the holes. If you bend the leads after they go through the holes the parts will stay put, and you can turn the board over to make solder connections. Lay out the parts so your circuit is intelligible and easy to check against the diagram. Don't be afraid to cut off excess length of leads, but leave about 1/4" or so minimum, for convenience in hooking on clip leads for measurements or trouble-shooting. Long loose leads can touch incorrectly and get in the way of circuit checking. Here, it is legal to tin while the wires are touching, but be sure you get good joints, with flowed solder. Big blobs are ugly, unnecessary, and can conceal a bad joint. It will be convenient to end up with output wires sticking up from the component side of the circuit board, which you can clip to. Make your actual wiring look as close to the schematic drawing as possible in order to facilitate debugging. Be neat, and your circuit is more likely to work correctly.

3.2 Check

Preliminary check: before turning on power

When you are done, carefully check your connections, making a check mark on the circuit diagram for each as you verify that it is correct. It is useful to check ELECTRICAL connections using the ohmmeter since bad solder joints can LOOK connected, but have no electrical contact. You need not check every solder joint, however: once you've tested a few and found them all good, you can trust your own soldering! Remember to turn your power supply off when debugging with the ohmmeter: we don't want an external voltage to overdrive the meter. You now have lots of bare wires on the bottom of the circuit board, so don't put it on top of electrical conductors like screwdrivers or metal tables.

Power On

Turn the pot to midscale, connect your meter on a reasonable voltage scale to the output wires, and plug in your transformer. Congratulations! –if it works. If the meter doesn't deflect, unplug the transformer and look for a wiring error. It helps to have a friend check if you can't see what's wrong. If you don't find your error, see whether the bridge rectifier is still working, by disconnecting it from the LM317. Starting from there, try to diagnose the problem by measuring circuit voltages. If you're baffled, bring your misbehaving circuit to the help lab.

Looking for "dropout"

Turn the pot in roughly 45 degree increments and record the output voltage. Does it change reasonably? Look at the voltage across the 360 ohm resistor, ($V_{\rm out} - V_{\rm ref}$), and see whether it stays at 1.25 volts as you turn the pot. To see best what is going on, make a plot with two curves: output voltage (V_{out}), and ($V_{out} - V_{ref}$), both plotted vs. pot setting. Is there a region where you are asking the output to go higher than it can manage?

Compare your maximum *output* voltage against the bridge rectifier voltage which is the regulator *input*. Given the '317's *dropout voltage* specification, is the maximum output voltage what you would expect? This "dropout" voltage—a minimum that the regulator must "drop" in order to function properly—underscores a point we made earlier: the regulator always delivers an output smaller than its input, soaking up the difference. (Note that this "dropout" voltage is not the same as the 1.25V difference that the device works to maintain; $V_{dropout}$ is a voltage difference between Input and Output; the $1.25V$ difference, in contrast, appears between Output and the "ADJ" terminal.)

4 Safety from Electrical Shock

4.1 Current Kills

The salty fluids in the human body (blood, lymph) are electrical conductors, much poorer than metals but far better than insulators like plastics or glass. The interior resistance of an arm, from hand to shoulder, can be estimated to be less than 100 ohms. Any voltage impressed across this internal resistance will cause currents to flow, and heat to be generated, sufficient to cause burns which destroy tissue for large enough currents and long enough times.

Much more significant, the nervous system and its means of control over muscles, including breathing and the heart, is electrochemical. Small externally applied currents can upset the signal rhythms, and do permanent damage, at energy releases far less than that for producing burns.

The easiest index of internal energy release to measure from outside is the current which flows through the body. Unless current flows there is no damage. Larger currents can be tolerated for shorter times.

Experience shows these results:

1. Below about 1/2 milliampere, entering current is not noticed. From that value up to ten milliamperes, the current is sensed, but no significant damage is expected. For a very brief time, say .01 seconds, up to about half an ampere is not damaging.

2. From about 5 milliamperes up to 20 milliamperes exposure for seconds may cause muscle spasm, making it hard to release a grip on a conductor and affecting heart and breathing rhythms. These frightening effects last while the current flows, but there is ordinarily no lasting damage.

3. Beyond 20 milliamperes there is LIFE-THREATENING DANGER. The chance of cardiac arrest is increasingly likely as currents get larger.

4.2 How to Avoid Shock

Think of what you are about to do before you do it; that is the only safe way. Estimate the voltage and current that can result from a mistake, and act cautiously, anticipating the possibility of a false motion or slip of the hand.

The resistance of dry skin is a very important protection at low voltages. Typically, over an ordinary contact area, the skin inserts 10k to 100k ohms between an outside conductor and the internal body fluids. Thus, at voltages below about 50 volts the skin provides safe current limiting - IF IT IS DRY. Be very wary of wet or sweaty hand contact.

When working with voltages of 100 volts or more, EXERCISE GREAT CARE. THIS OBVIOUSLY INCLUDES HOUSEHOLD A.C. POWER. Good contact can be lethal. Never work on live circuits unless it is absolutely necessary. If you must, proceed with great deliberation and caution. A famous rule is to *keep one hand in your pocket* because arm-to-arm current through the heart is far worse neurologically than local currents through one limb.

PREVENTION IS CENTRAL. Fast removal of a marginal contact may prevent serious injury; heart massage and artificial respiration after shock are worth the effort, but obviously are measures of last resort.

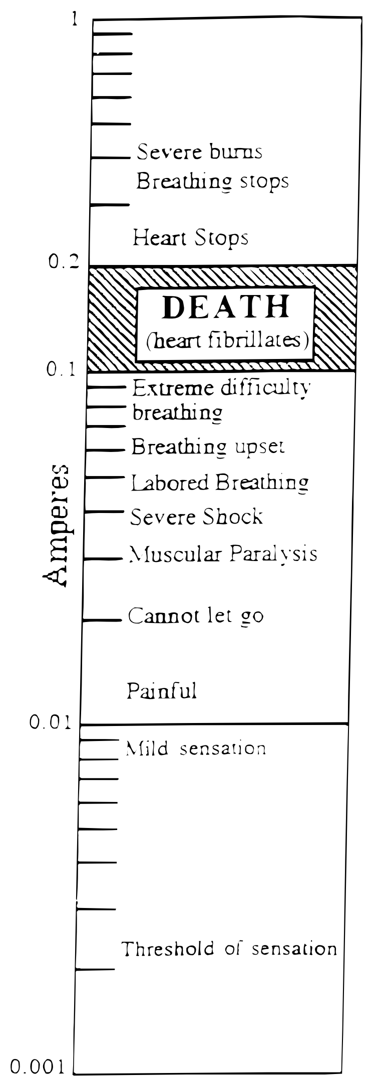
4.3 Relation to What You Will do in this Course

The wall transformer protects you from the danger of contact with household a.c. voltages, providing 12 volts a.c. at your circuits. Never even think of using a homemade connection to 120 volt a.c. power.

Experiments with AA batteries or your low voltage power supply are in the voltage range where the insulation resistance of your skin provides safe protection. But do not develop habits of carelessness that may cause trouble in other contexts. Think before you act.

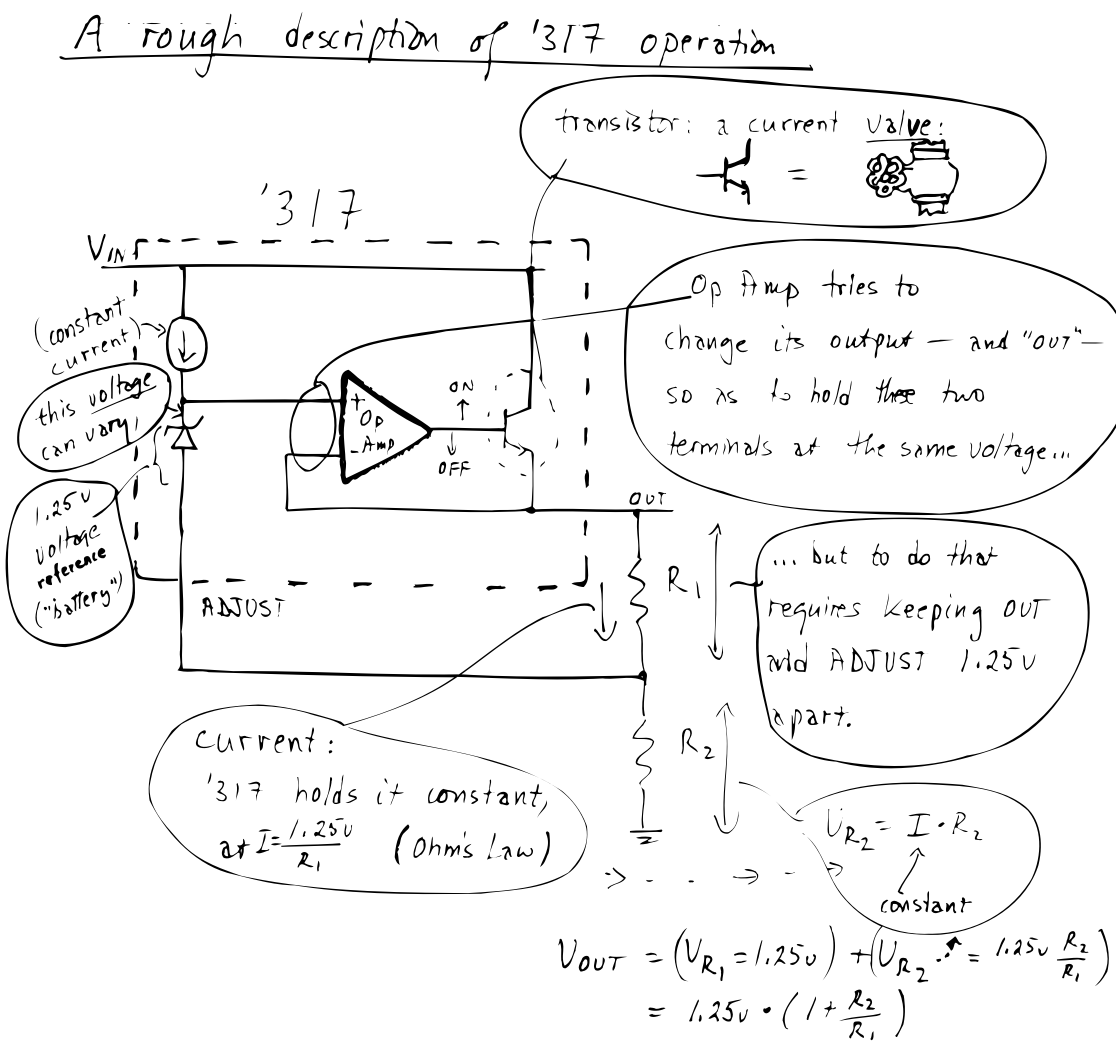
Throughout all the experiments of the course, the normal use of the apparatus you build will be safe. HOWEVER, IT IS POSSIBLE TO CREATE VERY GREAT HAZARDS BY IMPROVISED *INVENTIONS*. Do not connect several low voltage supplies in series. This is as foolish as the things you also might do with the household electrical gadgets at hand. If you are smart enough not to use an electric hair dryer in the bathtub, or poke around inside a TV set with its back off, exercise the same sense with the materials you make in this course.

The chart below reminds you of what current can do.



5 A Sketch of the Innards of the ’317 Voltage Regulator

And here’s a recapitulation of what’s going on within the ’317, in informal terms.



LM317 datasheet excerpt follows; a separate document, in Web version